Response of monopiles under cyclic lateral loading in sand

Nicolai, Giulio; Ibsen, Lars Bo

Publication date:
2015

Document Version
Accepted author manuscript, peer reviewed version

PO. ID 006

Response of monopiles under cyclic lateral loading in sand

Giulio Nicolai and Lars Bo Ibsen
Aalborg University, Denmark

AALBORG UNIVERSITET

Abstract

Currently the main design guidelines propose to reduce the lateral resistance of offshore piles when accounting for cyclic loading. The present work shows that such reduction has not occurred in the laboratory tests that have been performed. The experimental investigation is based on testing a small-scale monopile model in dense saturated sand. The experimental setup used to carry out the laboratory tests is able to apply thousands of load cycles and static loading to the monopile model. The purpose of the laboratory tests is to investigate the effects of the cyclic loading on the lateral resistance of the monopile. It is shown that the soil-pile system becomes stiffer and more resistant after applying cyclic loading, depending on the number of cycles.

Objectives

Offshore wind energy has a large potential for development although represents yet a small percentage of the total wind energy capacity. Large availabilities and high mean wind speeds make the offshore wind energy technology an attractive solution. Nevertheless, the costs for such technology are higher compared to the onshore converters and thus a cost reduction is a goal that has to be achieved. The foundation represents approximately one third of the total cost of an offshore wind turbine and therefore researches aimed at costs reductions are necessary. There are several foundation concepts for offshore wind turbines and the most common is the monopile foundation. Such foundation is a hollow steel pile that is driven into the seabed. The current design methodology of monopiles under lateral loading might be not properly formulated in the main design standards, i.e. API (2010) and DNV (2010). Indeed the design approach for offshore piles was proposed in the 1970s and developed by testing slender piles used in the oil and gas sector. Such typologies of piles have diameters in a range of 0.5 m to 2 m and have a flexible behavior, whilst piles for offshore wind turbines have diameters in a range of 4 m to 6 m and have a stiff behavior, as shown in Figure 1. Further, the current design method does not account for the number of cycles and was developed by analyzing experimental results of tests with less than 1000 cycles. In real offshore conditions, a wind turbine structure is subjected to millions of cyclic loads that induce to an accumulated rotation that might be critical for the turbine. Therefore, further investigations are necessary to fully understand the response of monopiles under cyclic lateral loading in order to improve the design guidelines. A more appropriate design methodology might lead to a reduction of the foundation size and hence to decrease the amount of material, achieving a reduction of the costs.

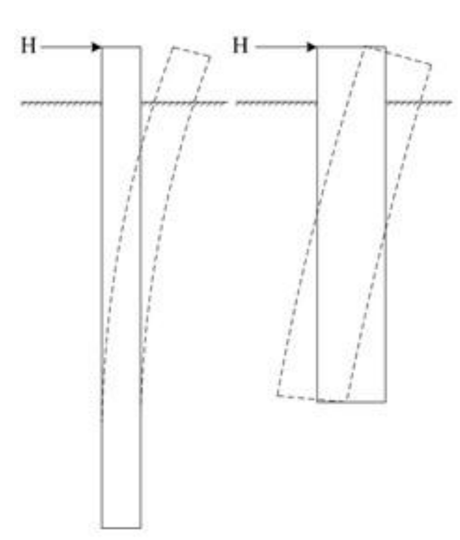

Figure 1. Different mode of deformation of a slender pile for oil and gas systems and a stiff pile for offshore wind turbines, under a lateral load H.

Experimental Setup

The test setup utilized for the experimental investigation is a 1g testing rig capable of performing static and cyclic tests and is depicted in Figures 2 and 3. The experimental tests have been carried out with Aalborg University Sand No.1, which is prepared dense with a relative density of 85% to 90% and saturated with water. The sand is the same from test to test and is prepared with a standard procedure before each test in order to ensure conditions of repeatability. The relative density of the sand is measured by carrying out small-scale Cone Penetration Tests before each test. The loads are applied to a steel bar that is bolted on the top of the pile after installing it in the sandbox. No pore pressures are developed during the tests, meaning that the response is drained. The monopile model has a diameter of 10 cm, embedded length of 50 cm and thickness of 5 mm, and represents a real monopile on a scale of 1:50 approximately.

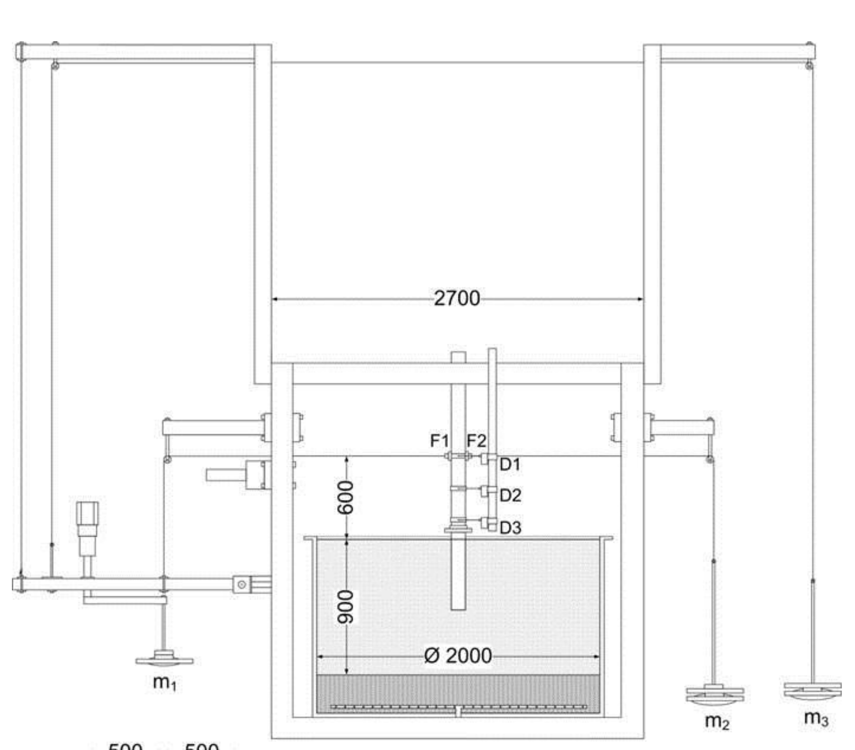

Figure 2. Sketch of the experimental setup. Dimensions are in mm. F_1 and F_2 are the load cells, D_1, D_2 and D_3 are the displacement transducers, m_1, m_2 and m_3 are the masses used to apply the cyclic loading.

Figure 3. Experimental setup.

Methods

Two non-dimensional parameters have been used to define the cyclic loading configuration, according to LeBlanc et al. (2010),

$$\zeta_b = \frac{M_{max}}{M_R} \quad (1)$$

$$\zeta_c = \frac{M_{min}}{M_{max}} \quad (2)$$

in which M_{max} and M_{min} are the maximum and minimum moments in a cyclic test and M_R is the ultimate capacity of the pile in a static test. ζ_b and ζ_c represent respectively intensity and symmetry of the cyclic load. The parameter ζ_c is equal to 0 for one-way loading and to -1 for two-way loading, as shown in Figure 4.

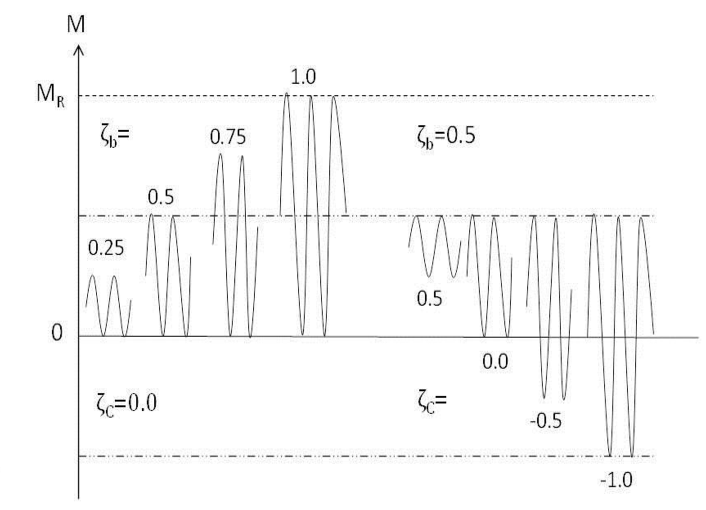

Figure 4. Cyclic loading configurations after LeBlanc et al. (2010).

Results

Eight cyclic tests with 10 to 50000 load cycles have been carried out and analyzed in the present work. Each cyclic test has been performed with ζ_b=0.3 and ζ_c=0. The post-cyclic capacity of the pile is the static ultimate resistance after applying cyclic loading and is achieved by performing a static test after a cyclic test. The post-cyclic capacity has been compared with the static capacity without applying cyclic loading. It can be seen in Figure 5 that in each test the capacity of the pile is increased after applying cyclic loading. In particular Figure 5 shows that the post-cyclic capacity of the piles is 10% to 20% larger than the static capacity, depending on the number of cycles. Indeed the capacity of the pile is increased of 10% after a cyclic test of 10 cycles and of 20% after 50000 cycles, approximately. This means that the increase in capacity is larger increasing the number of cycles. This is due to a compaction of the sand during cyclic loading, which induces the soil to become stiffer and more resistant. Further, the pile static capacity has been plotted in Figure 6 with the post-cyclic capacity of two tests of 100 and 10000 cycles. It is shown that the curves of the post-cyclic tests have a larger slope than the static test, meaning that the rotational stiffness is increased after applying cyclic loading. These findings are in contrast to the design guidelines proposed from current standards, which consider cyclic loads as reducing factors of the pile capacity.

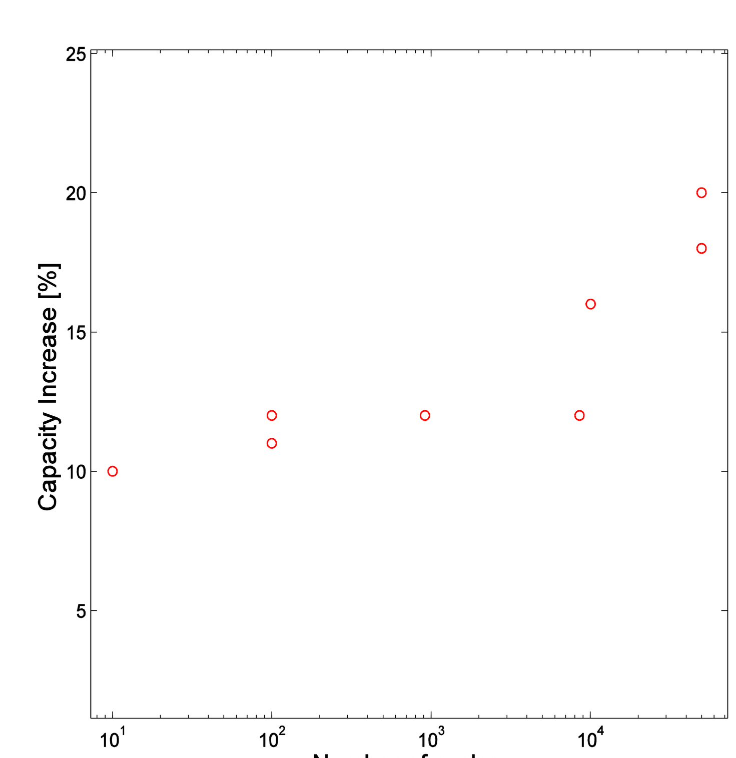

Figure 5. Increase of the ultimate capacity of the pile after applying cyclic loading.

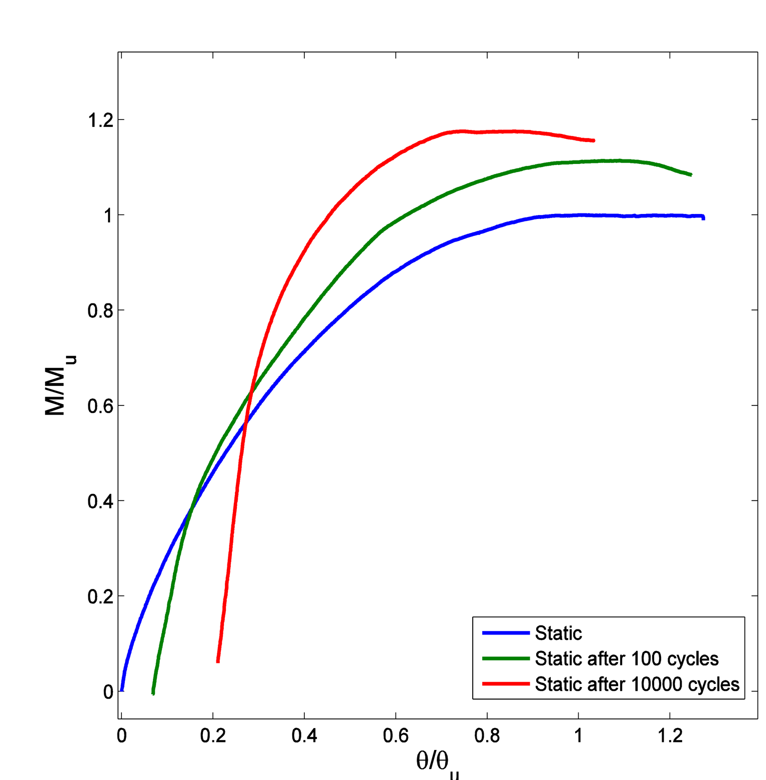

Figure 6. Capacity of the pile in a static test and in static tests after 100 and 10000 cycles. M_u and θ_u are the ultimate capacity and rotation in the static test without applying cyclic loading.

Conclusions

The present work provides results of an experimental investigation aimed at studying the effects of cyclic loading on the lateral resistance of monopiles. It turns out that the pile capacity is increased by 10% to 20% after applying cyclic loading. Further, it is proved that the number of cycles affects the capacity and stiffness of the pile. An example is provided where it is shown that the increase in stiffness and capacity of the pile varies with the number of cycles. These results confirm that current design methods are not capable to the capture the real response of monopiles under lateral loading. Moreover an increase of resistance might lead to reduce the dimensions of the monopile, e.g. diameter or length, thus achieving a decrease in the materials costs.

References

API (2010). "Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms-Working Stress Design, RP 2A-WSD", 21st edition, American Petroleum Institute.

DNV (2010). "Offshore standard DNV-OS-J101: Design of offshore wind turbine structures". *Technical report DNV-OS-J101*", Det Norske Veritas.

LeBlanc, C., Houlsby, G. and Byrne, B. (2010). "Response of stiff piles in sand to long-term cyclic lateral loading". *Géotechnique,* 60 (2), pp. 79-90.